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A synthesis of the European copper supply chain under the Critical Raw Materials Act

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ABSTRACT

The European Union's (EUs) Critical Raw Materials Act (CRMA) aims to strengthen the EUs resource resilience by increasing the autonomy of Critical Raw Material (CRM) supply through EU-based extraction, processing, and recycling, thereby reducing external dependencies and promoting a circular economy. Copper, a key CRM, faces growing demand that cannot be fulfilled by mining alone. This research analyzes the European copper supply chain under the CRMA and evaluates the role of recycling in meeting its requirements. An initial qualitative analysis suggests that recycling is the most promising solution to comply with the CRMA. The study develops a Mixed Integer Linear Programming (MILP) model to optimize the European copper recycling network under the CRMA recycling requirement and to validate the potential of recycling in a quantitative way. Results identify four optimal facility locations spread through Europe based on geographic centrality weighted by supply and demand quantities. Although the collection of European waste can feasibly satisfy the minimum recycling requirements as set out by the CRMA, changing regulations, disruptions, or changes in demand and external supply may lead to shortages. Improving recycling efficiency has therefore been marked as an important direction of future research.

1. Introduction

Modern supply chains face numerous challenges, including increasing supply disruptions and the growing importance of sustainability. In particular, the guaranteed long-term availability of Critical Raw Materials (CRMs) is under pressure. While demand for CRMs is expected to increase, Europe relies heavily on imports, often from third countries. To ensure economic resilience, the European Union (EU) addresses the risks associated with these strategic dependencies, especially after recent developments such as the COVID-19 pandemic and geopolitical conflicts. As a result, the EU prioritizes strategic autonomy and secure access to CRMs, which are essential for achieving the climate ambitions (European Commission, 2023).

Moreover, as sustainability has become a crucial concept, the United Nations' 2030 Agenda, along with its 17 Sustainable Development Goals (SDGs) introduced in 2015, has set new expectations for businesses to align their strategies and operations with these global goals (Wu et al., 2024). Furthermore, during the COP 28 UN Climate Change Conference in Dubai in 2023, it became clear that progress after the Paris Agreement was slow. The participating countries agreed on measures to accelerate action in these areas by 2030, urging governments to prioritize transitioning from fossil fuels to renewable energy sources (United Nations, 2024). As a result, many organizations are striving to integrate sustainability into their operations and supply chain management (Wu et al., 2024). This results in an increased demand for CRMs, as these materials are essential for products used in the energy transition, such as batteries, solar panels, and wind turbines. In response to these challenges, the EU has introduced regulatory frameworks such as the Critical Raw Materials Act (CRMA), which came into force in May 2024. The CRMA aims to strengthen the EU's resource resilience by increasing the autonomy of CRM supply through EU-based extraction, processing, and recycling, thereby reducing external dependencies and promoting a circular economy (Hool et al., 2023).

In this paper, we investigate the effects of the CRMA on a copper supply chain network. Copper is selected as the focus of this study for several reasons. First, its critical role in modern industries, particularly in electrification and clean energy technologies, makes copper an irreplaceable material in the energy transition (European Commission, 2023a). Second, it is one of the most recyclable metals, making it an environmentally sustainable resource. Recycled or secondary copper is indistinguishable from primary copper (International Copper Study Group (ICSG), 2024b). Other CRMs, such as lithium or rare earth

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elements, on the other hand, do not have a well-established recycling chain and lack publicly available data, making them less representative for this study. Finally, future copper demand is projected to exceed primary supply, as mining and processing capacities will not be sufficient to meet the requirements of the green transition (Peck and Sprecher, 2023). These factors jointly make copper both a strategically critical and methodologically representative material for studying recycling infrastructure design.

The pressing issue is not so much the depletion of copper or other critical metals, but rather the inability to secure them in time for the increasing future needs of industries. The timeline to develop new mines is substantial, often taking 10 to 20 years, and in addition, new mining projects in themselves will likely fail to meet environmental goals (Peck and Sprecher, 2023). Therefore, recycling is the most promising stage of the supply chain to meet the CRMA constraints, making a more detailed analysis of the choice options for industries is relevant. These options include the optimal number, locations, and capacities of recycling facilities within the EU, taking into account considerations of (future) copper supply and demand as well as the transportation costs. This analysis is conducted through a Mixed Integer Linear Programming (MILP), which allows us to evaluate which locations in Europe are most suitable for recycling facilities, given the proximity to the supply of scrap copper and the demand for recycled copper. Additionally, multiple scenarios, such as supply and demand fluctuations and disruptions, have been analyzed to assess the network's performance under varying conditions.

This study advances existing recycling network optimization research in three key ways. First, it introduces a policy-driven modeling framework that explicitly integrates the objectives of the EU CRMA into an MILP model. This framework not only quantifies the impact of regulatory targets on supply chain design but is also generalizable to other critical raw materials and geographic contexts. Second, the study provides a quantitative evaluation of how CRMA recycling targets influence costs, emissions, and resilience, translating the model outcomes into actionable perspectives for policymakers and industry, and further directions for research. Third, it offers geographic and infrastructure insights by identifying spatial imbalances in Europe's copper recycling network and highlighting underutilized regions as potential areas for resilience-enhancing investment. Together, these contributions bridge the gap between policy objectives, quantitative optimization, and practical design for CRM supply chains.

The paper is organized as follows: Section 2 presents a review of relevant literature and a qualitative analysis of the impact of CRMA regulations. Section 3 describes the methodology used for the optimization of recycling locations. Section 4 discusses the results evaluated on a realistic dataset of European supply and demand for copper. Section 5 concludes the key findings and future research directions.

2. Literature synthesis

The CRMA can be theoretically linked to both sustainable (Chinwego et al., 2025; Kudrenko et al., 2025) and resilient supply chain management (Guo, 2025; Wietschel et al., 2025). From a sustainability perspective, the Act aligns with the principles of Sustainable Supply Chain Management (SSCM) by promoting circularity, resource efficiency, and the reduction of environmental impacts. Through its targets for extraction, processing, and recycling within the EU, the CRMA operationalizes the goals emphasized in sustainability and circular economy literature. Simultaneously, the CRMA contributes to supply chain resilience by fostering diversification of CRM supply sources and enhancing regional processing and recycling capacities. These measures strengthen the robustness and adaptability of European CRM supply chains against external disruptions. The modeling framework developed in this study applies these theoretical principles by quantifying how recycling expansion and optimized facility locations can reinforce both sustainability and resilience in CRM supply chains.

2.1. Critical Raw Materials Act and EU regulations

The EU defines Critical Raw Materials (CRMs) as materials of great economic importance to Europe. These materials are highly susceptible to supply chain risks due to growing global demand, particularly as economies transition towards decarbonization. This especially applies to metals and minerals that cannot be substituted with more common alternatives and have a risk of supply disruption. If the supply of these materials is disrupted, it can lead to severe negative economic consequences (EU, 2023a). Raw materials provide an industrial foundation for various goods and applications utilized in daily life and advanced technologies. However, access to certain raw materials is becoming an increasing concern both within the EU and globally. Also, the supply chain for critical materials is vulnerable and in many cases highly concentrated.

Materials like lithium and rare earths are vital for key products crucial to Europe's green and digital future, including solar panels, batteries, wind turbines, electric vehicles, and computer chips (EU, 2023a; European Commission, 2023a). But even the availability and supply of more common materials, such as copper, might be under pressure. In order to get insight into potential supply challenges, the European Commission has established a list of CRMs, which is checked and updated every three years (Mathieux et al., 2018).

In May 2024, the Critical Raw Materials Act came into force as part of its broader strategy to strengthen the EU's resource resilience (Hool et al., 2023). Moreover, CRMA is part of the Green Deal Industrial Plan, next to the European Green Deal, a transformative initiative in response to the Sustainable Development Goals (SDGs), introduced by the United Nations in 2015. The Green Deal focuses on achieving climate neutrality, promoting a circular economy, and reducing emissions. At the same time, the Industrial Plan enhances the competitiveness of zero-emission industries and supports net-zero technologies (Longo and Cardillo, 2024).

The Critical Raw Materials Act aims to enhance the EU's capacity for CRMs, reduce dependency on external sources, boost preparedness, and promote circularity and sustainability within the supply chain (EU, 2023a). Key guidelines for 2030 set by the Act include:

1. At least 10% of the EU's annual consumption must come from EU-extraction;
2. At least 40% should be processed within the EU;
3. At least 25% must be recycled;
4. No more than 65% of annual consumption can originate from a single third country.

This legislation also aims to reduce administrative burdens by simplifying the approval processes for CRM projects while maintaining strong social and environmental standards. Additionally, selected strategic projects will benefit from financial support and reduced permitting timelines (European Commission, 2023a). Furthermore, EU member states must enhance the collection and recycling of CRM-rich waste and investigate the recovery of these materials from extractive waste. The Act empowers the Commission to establish environmental footprint regulations for CRMs. This will help to increase the circularity and sustainability of CRMs placed on the EU market, fostering informed customer choices about products containing CRMs (EU, 2023b).

In addition to the Critical Raw Materials Act (CRMA), the EU has introduced several other related regulations, including the Corporate Sustainability Reporting Directive (CSRD), the Corporate Supply Chain Due Diligence Act (CSCDDA), the Ecodesign for Sustainable Products Regulation (ESPR), the Carbon Border Adjustment Mechanism (CBAM), the EU Battery Regulation (BATT2), and the Regulation on Deforestation-Free Products (EUDR). In Table 1 an overview of these regulations is provided.

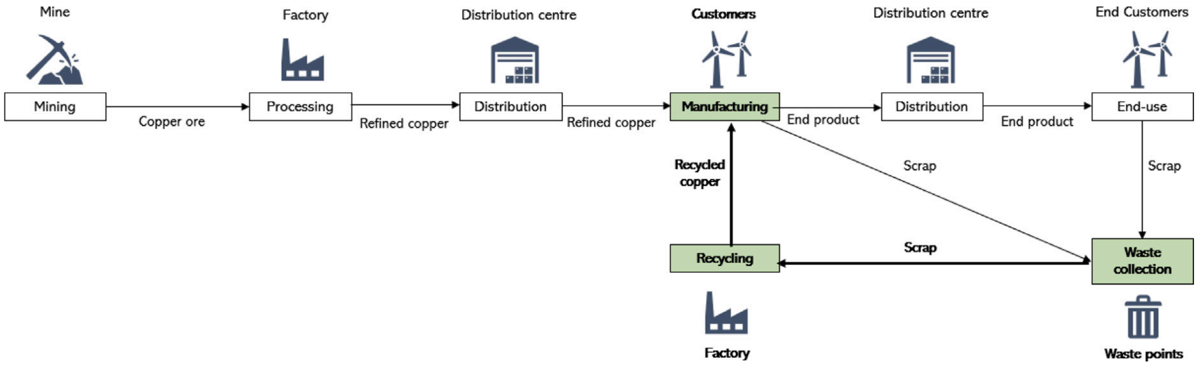

Fig. 1. Copper supply chain (focus area of the study in green).

Table 1
Related relevant regulations introduced by the EU.

CSRD	Requires large and publicly listed companies to report on the social and environmental risks they encounter regularly, as well as the impacts of their activities on people and the environment (European Commission, 2024a).
CSCDDA	Promotes sustainable and responsible corporate behavior to facilitate a fair transition towards a sustainable economy (European Commission, 2024f).
ESPR	Aims to make sustainable products within the EU norm (European Commission, 2024e).
CBAM	Serves as the EU's tool to assign a fair price to the carbon emissions associated with the production of carbon-intensive goods entering the EU, thereby encouraging cleaner industrial practices in non-EU countries (European Commission, 2024g).
BATT2	Ensures that batteries sold in the EU market are sustainable and circular throughout their entire lifecycle (European Commission, 2024d).

2.2. Copper supply chain

Copper is a CRM, a highly recyclable material with extensive industrial applications, particularly in electronics, renewable energy, and transportation (International Copper Study Group (ICSG), 2024b). As can be seen in Fig. 1, the copper supply chain consists of multiple stages, including mining, processing, distribution, manufacturing, waste collection, and recycling. The CRMA will significantly influence the copper supply chain, as summarized in Table 2, as a result of strategic reorientation. Rather than a focus on global cost-efficiency (Glencore, 2024b), the focus should transition to one centered on EU autonomy, circularity, emissions reduction, and regulatory compliance (EU, 2023a).

Firstly, sourcing and processing are expected to shift more into the EU, with targets of at least 10% sourcing and 40% processing (EU, 2023a), compared to the previous reliance on non-EU countries (Wincewicz-Bosy et al., 2021). Recycling practices should also become more localized, moving to 25% recycling within the EU (Hool et al., 2023). Before, European scrap was often exported to non-EU countries for external recycling (Henckens and Worrell, 2020). Product design will have to prioritize recyclability. Emissions are expected to decrease due to shorter, intra-EU logistics (Teske et al., 2022), which aligns with the aforementioned location decisions. Permitting procedures for opening mines, processing facilities, and recycling facilities, previously fragmented and slow (Hool et al., 2023), will be fast-tracked for strategic projects (Tröster et al., 2024). Market conditions will shift as regulatory incentives, such as EU funding and joint purchasing, are introduced (European Commission, 2023b). Stakeholders are expected to take on greater responsibilities, including mandatory transparency and reporting on critical raw materials. Finally, EU-based recycling may bring higher costs compared to low-cost recycling (and related transport) outside the EU (Tröster et al., 2024).

Table 2
Copper supply chain before and after the CRMA.

	Before CRMA	After CRMA
Sourcing & processing	Mostly outside EU (Wincewicz-Bosy et al., 2021).	10% sourced, 40% processed in EU (EU, 2023a).
Recycling share/location	45% recycled globally; EU scrap often exported (Henckens and Worrell, 2020).	25% recycled in EU; focus on local scrap (Hool et al., 2023).
Strategic focus	Global cost-efficiency (Glencore, 2024b).	EU autonomy, circularity, emissions, compliance (EU, 2023a).
Design & disassembly	Products not designed for recyclability.	Design for recycling prioritized.
Emissions & transport	High due to global logistics (Teske et al., 2022).	Lower via localized EU logistics (Teske et al., 2022).
Permitting	Long, fragmented, nationally led (Hool et al., 2023).	Fast-tracked for strategic projects (Tröster et al., 2024).
Market incentives	Few regulatory incentives.	EU funds, joint purchasing, strategic stockpiles (European Commission, 2023b).
Stakeholder role	Limited governance role (Hool et al., 2023).	Greater responsibility, transparency, CRM reporting.
Recycling costs	Focus on low-cost exports.	Higher costs for EU-based recycling (Tröster et al., 2024).

2.3. Why should the focus be on recycling copper

As is depicted in Fig. 2, the copper demand is expected to exceed the copper supply around 2026, which will result in a supply gap. Moreover, the timeline to build new mines and expand raw material extraction in the EU is not viable, as developing a new mine typically takes 10 to 20 years (Peck and Sprecher, 2023). Thus, there should be a **focus on recycling**, reducing, reusing and repairing as the lengthy process of opening new mines makes it impossible to meet future demand and the CRMA's targets.

As reducing, reusing, and repairing are the responsibility and in the power of the customers and end customers of natural resource companies,[1] the focus of this study is recycling, which is in the power of natural resource companies. By increasing the amount of copper

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[1] Customers (industrial and manufacturing companies) are responsible for ensuring their products are repairable or reusable and end customers are responsible for reducing their buying behavior and repairing instead of buying.

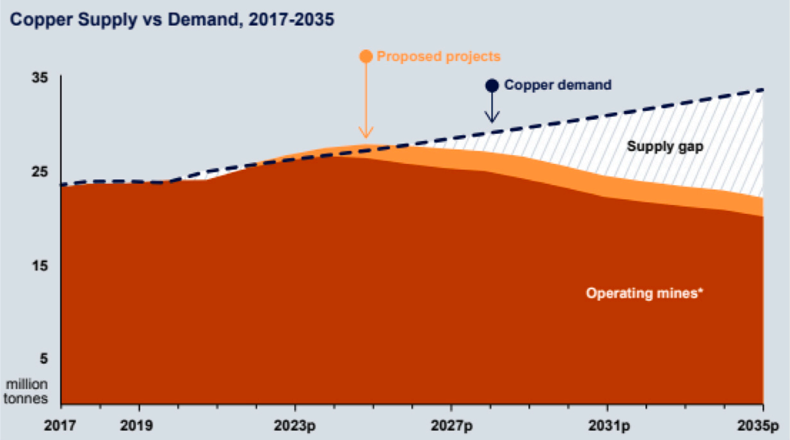

Fig. 2. Copper supply vs. Demand, 2017–2035 (Mackenzie, 2024).

recycled, ensuring that at least 25% is recycled within the EU, the benchmark can be met. However, the demand for recycled copper is expected to rise, presenting an opportunity for market expansion. When it is timely anticipated on the CRMA by optimizing the recycling network in Europe, natural resource companies can enhance their market position.

Focusing on recycling will have the following advantages:

- The recycling expansion would not only comply with the CRMA but also position companies advantageously in the European market;
- By increasing the supply of recycled copper, companies can mitigate the challenges associated with developing new mines within the EU, which will not be feasible in the short term;
- Recycling copper consumes less energy and reduces emissions than primary extraction. Additionally, because the recycling occurs within Europe, transportation emissions will be reduced. When reporting on its environmental performance, this will be beneficial to demonstrate compliance with the CRMA and build trust with stakeholders. The reduction in emissions would be beneficial for its scope 1 and 3 emissions.[2]

Nevertheless, it is crucial to note that recycling also faces several challenges. One major difficulty lies in the collection and processing of copper scrap. Modern devices are designed for efficiency and durability rather than recyclability, making disassembly complex and often unprofitable. Additionally, mixed-material components can make copper recycling difficult, as separation is difficult. Without proper pre-separation techniques, valuable raw materials may be lost or underutilized (Okon Recycling, 2025).

Furthermore, to optimize the recycling network, all European copper scrap streams must be identified and evaluated for economic feasibility. Currently, significant portions of European scrap are exported to countries due to lower processing costs (EuRIC AISBL, 2022). Thus, the recycling industry must be strengthened by ensuring higher economic feasibility of recycling within Europe (which will potentially be the result of the CRMA).

Also, companies should shift towards material-focused recycling instead of focusing only on reusing scrap within specific product groups. Rather than rebuilding an identical product from recycled components, businesses should prioritize extracting materials like copper and reintegrating them into the broader supply chain .

3. Location of recycling facilities

With an increased focus on recycling, two questions arise:

1. Can European demand for copper be met by supply from European recycled copper?
2. Where should recycling facilities be constructed to minimize the costs of operating facilities and transporting scrap and recycled copper to and from facilities, respectively?

To answer these questions, we construct an MILP to determine the optimal recycling-facility locations given realistic cost parameters, expected supply, and expected demand. Through this model, we determine the optimal facility locations, their capacity, and the optimal flow through the constructed recycling network.

The problem is formulated in Section 3.1 and the parameters are tuned according to available data sources in Section 3.2.

3.1. Problem formulation

We consider a set of potential recycling facilities I, a set of defined waste points J (i.e., sources for scrap copper), and a set of customer locations (i.e., users of recycled copper) K. Every waste location $j \in J$ produces a total of W_j tonnes of scrap copper, and every customer $k \in K$ has a demand of D_k recycled copper. Out of this demand, a minimum fraction λ has to come from European recycled copper. The facilities operate at a pre-determined efficiency of η and have a maximum recycling capacity of $C_{\max}$ measured in tonnes of scrap. Which facilities to open depends on the fixed costs of a facility $i \in I$ defined as f_i, the variable costs per ton of production v_i, and the transportation costs between two locations m and n, defined as t_{mn}, where m and n could be waste locations, customer locations or processing locations.

We decide which facilities to open through binary decision variables x_i for $i \in I$, and their corresponding capacity through decision variables z_i. The number of tonnes transported between locations m and n is defined as linear decision variable y_{mn}. A summary of the notation is given in Table 3. A formulation of the problem is given in (1)–(8).

$$\min \quad \sum_{i \in I} (f_i x_i + v_i z_i) + \sum_{m \in J \cup I} \sum_{n \in I \cup K} t_{mn} y_{mn} \tag{1}$$

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[2]

- Scope 1: Direct emissions from owned or controlled sources, for instance, natural resource or recycling operations;
- Scope 2: Indirect emissions from the generation of purchased energy;
- Scope 3: All other indirect emissions occurring in the value chain, including both upstream and downstream activities, for example, transportation costs (Teske et al., 2022).

Table 3
Mathematical model.

Sets and indices		
i	Index for recycling facilities	$i \in I$
j	Index for waste points	$j \in J$
k	Index for customer locations	$k \in K$
Parameters		
W_j	Waste at j	[ton]
D_k	Demand at k	[ton]
f_i	Fixed cost of facility i	[€]
t_{mn}	Transport costs from location m to location n	[€/ton]
v_i	Variable costs at i per ton of production	[€/ton]
λ	CRMA coefficient	[fraction, $0 < \lambda \leq 1$]
η	Recycling efficiency	[fraction, $0 < \eta \leq 1$]
$C_{\max}$	Facility max capacity	[ton]
Decision variables		
x_i	Facility i open (1) or closed (0)	[binary]
y_{mn}	Copper transported $m \rightarrow n$	[ton]
z_i	Capacity at i	[ton]

Subject to:

$$\sum_{i \in I} y_{ji} \leq W_j \qquad \forall j \in J, \tag{2}$$

$$\sum_{i \in I} y_{ik} \geq \lambda D_k \qquad \forall k \in K, \tag{3}$$

$$\sum_{j \in J} \eta y_{ji} = \sum_{k \in K} y_{ik} \qquad \forall i \in I, \tag{4}$$

$$z_i \leq C_{\max} x_i \qquad \forall i \in I, \tag{5}$$

$$\sum_{j \in J} y_{ji} \leq z_i \qquad \forall i \in I, \tag{6}$$

$$x_i \in \{0, 1\} \qquad \forall i \in I, \tag{7}$$

$$y_{ji}, y_{ik}, z_i \geq 0 \qquad \forall i \in I, j \in J, k \in K. \tag{8}$$

The objective function, Eq. (1), minimizes the total costs by combining three components: fixed costs per facility, variable cost per tonne of production at a facility and transportation costs. Details on each component of the cost function are included in Section 3.2. Constraints (2) ensure that the total waste transported from each waste point does not exceed its availability. Constraints (3) enforce compliance with CRMA by requiring that at least 25% of customer demand is met through recycled copper. Constraints (4) ensure that the amount of recycled output corresponds to the waste input times the recycling efficiency. Through these constraints, we implicitly assume that all recycled copper is actually consumed by customers. If customers only consume the minimum required amount, the equality and inequality signs of Constraints (3) and (4) can be switched. Constraints (5) ensure that the capacity of an opened facility is within the maximum, while the capacity of a closed facility is forced to 0. Constraints (6) ensure that the total amount of scrap delivered to an opened facility can actually be processed there. Last, constraints (7) and (8) define the domain of the decision variables, ensuring non-negative values.

3.2. Parameter tuning

The parameters used in the model are derived from a case study on a leading natural resource company, for which the demand data was available online. Furthermore, the waste points (W_j) were determined based on Europe's 15 highest copper-consuming countries (Statista, 2023). Moreover, copper industrial activity zones were identified based on Eurostat's NUTS-3 employment dataset in the industrial sector (Eurostat European Union, 2024). The dataset is filtered for the category [B-E] Industry and the NUTS 2 regions in 2021. Furthermore, only the largest copper-consuming countries were selected, and the data was reduced to areas with more than 100,000 employees, leading to a dataset of 105 datapoints. Subsequently, copper consumption per city is estimated by calculating the city's workforce proportion relative to the national workforce and multiplying it by the country's industrial copper consumption (30% of total copper consumption) (International Copper Study Group (ICSG), 2024a; Statista, 2023). Copper waste per city is then derived by applying a 56% collection rate to the estimated consumption (International Copper Association, 2022).

For the demand locations (D_k), cities with a copper consumption exceeding 12,000 tonnes per year were selected, resulting in 18 customer locations. The European copper demand data of the case study was used (Glencore, 2024a). The demand per city was proportional to that city's total copper consumption share. The AIMMS Center of Gravity (CoG) tool was used to determine potential recycling locations (i). Based on balancing distances and volumes (and thus transportation costs) between waste points and customer locations, 30 candidate recycling facility locations were generated.

All parameters were derived from reliable sources to ensure realistic modeling. The fixed costs consists of a depreciation, subsidy, risk and internal rate component, as follows:

$$f_i = \frac{A_i}{\text{DEPR}} - \text{Subsidy}_i + Risk_i + IR_i$$

Baseline costs (A_i) were based on Swedish facility data from Tadaros et al. (2022), adjusted for other cities using construction cost indices from Arcadis (2023) and a depreciation factor ($DEPR$) derived from Tadaros et al. (2022). Moreover, subsidies ($Subsidy_i$) are project dependent (European Commission, 2024c) and were therefore estimated at 10% of A_j. Risk costs ($Risk_i$) were based on the INFORM index and normalized to 1%–2% of A_j (European Commission, 2024b). Lastly, the internal rate (IR_i) was set at 9% of A_j, averaging values from similar facility investment studies (Tadaros et al., 2022; Sunaryo et al., 2020).

The transport costs includes the value of time, speed and wiggle factor, as follows:

$$t_{mn} = (B_{mn} + \frac{\text{VoT}}{\text{Speed}}) \cdot d_{mn} \cdot (1 + WF)$$

Transport costs (B_{mn}) were taken from Persyn et al. (2022), considering distance, time, and infrastructure and a 40-ton truck with a load of 25 tonnes. VoT (VoT) was calculated using cargo value-based in-transit costs from Kouwenhoven et al. (2023). Distances (d_{mn}) were computed in AIMMS using LocationIQ, adjusted with a wiggle factor (WF) from Domínguez-Caamaño et al. (2016), to correct for the straight line distances. The CRMA coefficient (λ) was set to 25% as the CRMA requirement (EU, 2023a). Maximum facility capacity (C_{max}), average speed ($Speed$), and recycling efficiency (η) were taken from Tadaros et al. (2022), Persyn et al. (2022), and International Copper Association (2022), respectively. Costs per tonne (c_i) include labor per country from Eurostat (2024), combined with processing rates from Recycling Today (2024).

Compatibility of the datasources has been analyzed qualitatively, and quantitative sensitivity analyses were performed on all key parameters, including maximum facility capacity, transport costs, fixed costs, and demand and supply fluctuations. Those parameters for which interesting fluctuations were observed are included in the sensitivity analysis in Section 4.

4. Results

To evaluate how the CRMA influences optimal recycling locations, the model described in Section 3 has been evaluated through a realistic dataset. Model parameters have been tuned through a combination of open-source data and scientific sources, as described in Sections 3.2 and 4.1. The optimal supply chain configurations under the baseline scenario are evaluated in Section 4.2. Thereafter, a sensitivity analysis is performed on the minimum recycling requirement λ in Section 4.3, the recycling efficiency η in Section 4.4 and potential fluctuations in demand in Section 4.5.

Table 4
Overview datapoints parameters.

Parameter	Value	Source
DEPR	30 years	Tadaros et al. (2022)
Speed	90 km/h	Persyn et al. (2022)
η	0.56	International Copper Association (2022)
λ	0.25	EU (2023a)
VoT	0.789 €/ton/h	Kouwenhoven et al. (2023)
WF	0.33	Domínguez-Caamaño et al. (2016)
$C_{\max}$	50,000 tonnes/year	Tadaros et al. (2022)

4.1. Data description

An overview of the datapoint of the parameters can be found in Tables 4 and 5. Table 4 provides the parameters that are assumed to be constant for the entire network. Sensitivity analyses on the minimum fraction of recycled copper for each customer λ and the recycling efficiency η are performed in Sections 4.3 and 4.4, respectively. Table 5 displays the parameters that vary across the network. A detailed overview of the data is given in the Appendix. Summary statistics are given to shed light on their influence on the total supply chain configuration. Customer demand includes 18 data points, representing demand quantities at different customer locations. On average, demand is equal to 10,000 tonnes per year, ranging between 5000 and 15,000 tonnes. Variable costs are country-dependent and therefore consist of 8 data points, reflecting the facility locations in 8 different countries. Fixed costs, subsidies, risk values, and internal rates are tied to recycling facilities, each containing 30 data points corresponding to the 30 facilities considered. The number of facilities was chosen as a balance between computational efficiency and solution accuracy. Studies in facility location modeling typically use candidate sets with 10 s of potential facility locations. Adeleke and Olukanni (2020) provide a review of facility location problem applications, specific to waste management, where the number of candidate locations is often between 20 and 50. For our case, a sensitivity analysis showed diminishing improvements in objective value beyond 30 candidates, indicating that additional points contributed marginal gains in solution quality while substantially increasing computational cost. Transport costs are also facility-dependent, with 30 data points (transport costs to and from a recycling facility are assumed to be the same). Clearly, the baseline costs A_i are the largest fixed cost component. Nevertheless, subsidies, risks and internal rates may cause deviations.

4.2. Optimal locations

For the base scenario described in Section 4.1, the model reports an optimal number of four facilities, located as depicted in Fig. 3 with a joint capacity of approximately 152,000 tonnes. The capacity is distributed among these facilities as shown in Table 6. The results emphasize that waste availability and regional demand are key drivers in determining optimal facility locations and capacities. Stuttgart operates at full capacity due to its central location, enabling efficient collection and distribution despite the highest fixed costs. Geithain also benefits from its position but faces higher transport costs due to longer distances. Bologna serves northern Italy efficiently but runs below capacity because of high collection costs. Barcelona has the lowest capacity, limited by local waste supply and demand, resulting in the lowest transport costs but making it less suitable for scaling up.

When allowing the maximum capacity to increase to 200,000 tonnes compared to 50,000 tonnes, all supply and demand will be gathered in a single facility in Stuttgart, limiting the total costs to only 25 million euros. This is an obvious result given the economies of scale of using a single facility. Nevertheless, this would reduce network resilience in case of outages. Determining the optimal number of facilities should therefore be a decision that is not only influenced by costs, but also by resilience.

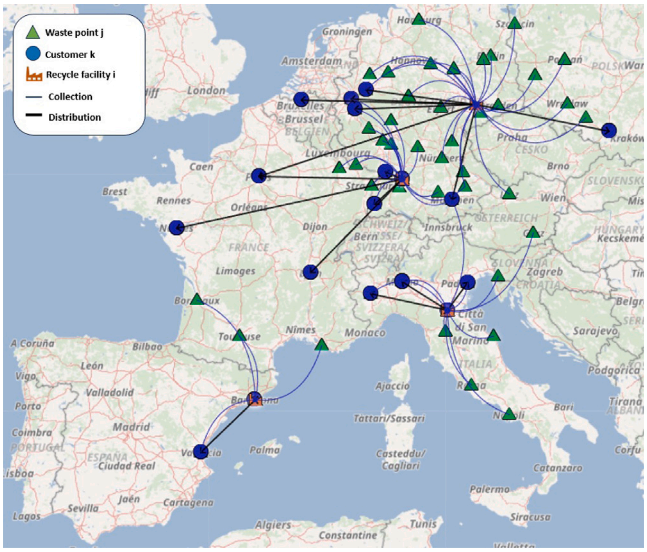


Fig. 3. Optimal recycling network, active nodes.

Fixed costs are the highest cost driver, contributing 60%, transport costs second with 30.7%, and variable costs have the lowest impact (9.3%). Within transport costs, waste collection is more expensive than distribution due to the need to source from many waste points, while customer locations are more concentrated. These results intuitively align with the current situation where most of the recycled copper is imported from outside the EU. Given the relatively low transport costs compared to the fixed costs, importing recycled copper from countries where fixed costs are lower can give them a competitive advantage.

To evaluate the resilience of the proposed recycling network, we study outages of local facilities. First of all, it is clear that with a maximum capacity of 50,000 tonnes at all facilities and a total demand of more than 150,000 tonnes, the outage of a facility will lead to unfulfilled demand. On top of that, reallocated production to other facilities lead to an increase in costs of between 4% and 25%. This increase is mainly caused by an increase in transportation costs, as less centralized facilities remain available.

4.3. Influence of minimum recycling requirement

The CRMA coefficient λ determines the minimum share of demand that must be met through recycled copper. Current regulations state that at least 25% of the used copper must be recycled in Europe, defining the baseline value of λ. The optimal locations of the facilities and the associated costs are given in Table 7. A maximum of $\lambda = 41\%$ is used, as beyond this value, demand exceeds supply and thus no feasible solution can be found. When the requirements are set lower than 25%, the number of recycling facilities also decreases. Naturally, a lower requirement would also come with lower overall costs, because recycling outside the EU is still cheaper, even taking into account transport costs. On the other hand, when the requirements increase, more demand has to be fulfilled, leading to the need for, and in the model thus the opening of, additional facilities. If regulations were to demand 30% recycled copper in Europe, Dortmund and Katowice would become active, and at 41%, the network expands to five facilities. Similar to the baseline scenario, facilities are geographically distributed throughout Europe. Raising the minimum recycling share would also result in other cost increases, mainly through collection costs (i.e., transportation from waste points to the recycling facilities), as more copper must be sourced from further waste locations. Fixed and distribution costs also rise due to the need for additional capacity and transport.

Table 5
Summary statistics of parameters.

Statistic	D_k	B_{mn}	A_i	$Subsidy_i$	$Risk_i$	IR_i	v_i	W_j
Count	18	30	30	30	30	30	8	105
Minimum	5937	0.0638	87,200,000	8,720,000	1,090,000	7,848,000	5.25	136
Maximum	15,836	0.2368	261,600,000	26,160,000	5,232,000	23,544,000	26.61	18,287
Range	9899	0.1730	174,400,000	17,440,000	4,142,000	15,696,000	21.36	18,152
Mean	8456.134	0.1055	174,290,000	17,429,000	1,992,753	15,479,100	17.44	4,297
Median	7534	0.0912	189,000,000	18,900,000	1,817,000	15,043,500	19.41	3,596
Std. Dev.	2694	0.0484	42,959,043	4,295,904	869,563	3,724,193	7.57	3,170

Note: This table displays summary statistics for the parameters that are location dependent. The second column denotes the customer demand in tonnes (D_k). The third column denotes the transport costs (B_{mn}). The fourth column denotes the fixed costs baseline (A_i). The fifth column denotes the subsidy ($Subsidy_i$). The sixth column denotes the risk ($Risk_i$). The seventh column denotes the internal rate (IR_i). The eighth column denotes the variable costs of production (v_i). Demand is given in tonnes, and all others are costs given in euros. Variable costs are measured per ton of production and transportation costs are measured per ton, per kilometer.

Table 6
Capacity and costs per opened facility.

Facility	Capacity	Fixed	Variable	Collection	Distribution	Total
Barcelona	16,600	4,800,000	230,000	860,000	290,000	6,200,000
Bologna	39,200	5,100,000	660,000	1,680,000	740,000	8,200,000
Geithain	46,400	3,900,000	1,080,000	2,040,000	2,100,000	9,100,000
Stuttgart	50,000	6,300,000	1,170,000	1,130,000	1,490,000	10,100,000
Total	152,200	20,200,000	3,140,000	5,720,000	4,620,000	33,600,000

For every opened facility, this table shows the capacity of that facility in tonnes in the second column. The other columns denote the fixed costs, variable costs, transportation costs of collection and distribution and the total costs, all in euros.

Table 7
Facility locations and cost breakdown for varying CRMA requirements.

λ	#	Locations	Fixed	Variable	Collection	Distribution	**Total**
10%	2	Bologna, Geithain	9,010,600	1,241,400	1,940,700	3,093,100	15,285,800
25%	4	Barcelona, Bologna, Geithain, Stuttgart	20,153,900	3,140,200	5,718,600	4,621,000	33,633,700
30%	4	Bologna, Dortmund, Stuttgart, Katowice	21,843,200	3,442,400	6,564,700	6,565,600	38,415,900
41%	5	Barcelona, Bologna, Dortmund, Stuttgart, Katowice	26,686,500	4,274,300	16,347,900	7,905,300	55,214,000

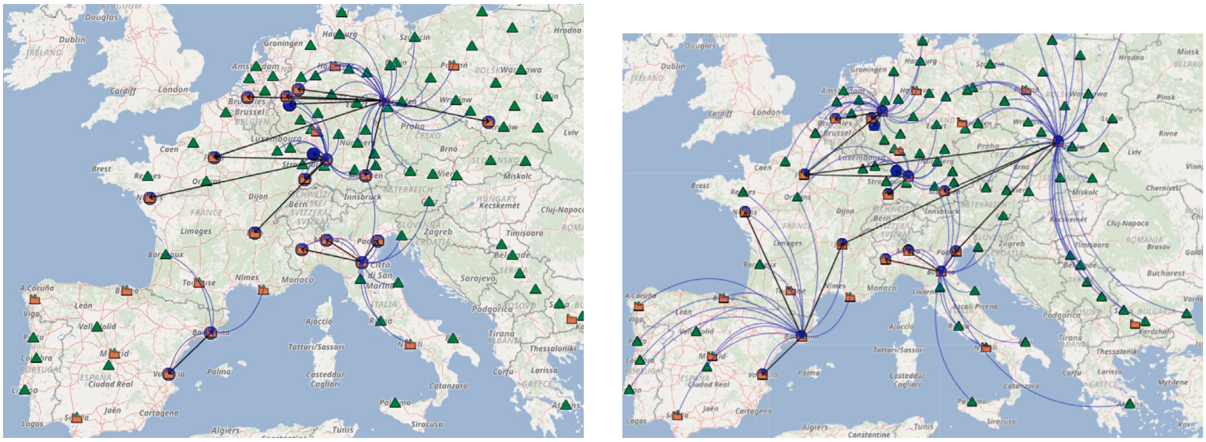
Note: The second column denotes the number of facilities, with their specific locations given in the third column. The other columns give an overview of the costs associated to this scenario. All costs are given in euros.

Interestingly, at the current recycling efficiency η, the European network can accommodate a recycling requirement of 41% by increasing the number of recycling facilities. Looking at Fig. 4, further facilities are used in case λ increases to 41%. Specifically, we can see that all waste sites are used in this case. This also supports the fact that for an increase beyond 41%, European recycled copper does not suffice to meet the CRMA requirements. Beyond this, no feasible network configuration can be found, given that the minimum required recycled copper to satisfy the CRMA requirement is higher than all available required copper in the network. This indicates that if regulations change, external copper supply decreases, or even if cost configurations change, striving for an increase in the recycling efficiency is absolutely essential.

4.4. Influence of recycling efficiency

Recovering copper from modern devices can be challenging and costly due to complex product design. These factors directly impact recycling efficiency (η), the amount of reusable copper that can be extracted from a certain amount of scrap materials. As illustrated in the previous section, recycling efficiency may even influence the overall feasibility of meeting the minimum recycling requirements. To further evaluate the effect of recycling efficiency on the operational costs and network configurations, we perform a sensitivity analysis on η. A baseline scenario of 56% is used, as supported in Section 3.2. The optimal locations of the facilities and the associated costs are given in Table 7. Similar to the previous analysis, when the recycling efficiency is too low, recycling copper can no longer satisfy the minimum CRMA requirement. In this case, the limit lies at $\eta = 34\%$.

Interestingly, the number of locations is relatively constant. At lower efficiencies, Dortmund is chosen as a location in stead of Stuttgart. When considering Fig. 5, it is clear that Dortmund is geographically more central for the new waste that is to be collected from North-Western Europe, whereas Geithain takes on more waste from Eastern Europe. Similar to the previous analysis, waste has to be collected from more locations when the efficiency drops to fulfill the same demand. On the other hand, an increase in efficiency allows to amount of collected waste to be reduced, which can therefore be taken from closer locations. From 56% efficiency onward, the network remains stable, with facilities in Barcelona, Bologna, Geithain, and Stuttgart. As recycling efficiency increases, the amount of usable copper extracted from waste increases proportionally, resulting in lower transportation costs. This is reflected in the cost reduction in Table 8. Clearly, only the transportation costs of waste to the recycling facilities are reduced, as the amount of recycled copper remains constant (with minor changes in locations causing the small change in distribution costs). Overall, the results further highlight the important role of recycling efficiency. Higher efficiencies enable a more cost-effective network, while lower efficiencies not only challenge feasibility but also drive up costs significantly.



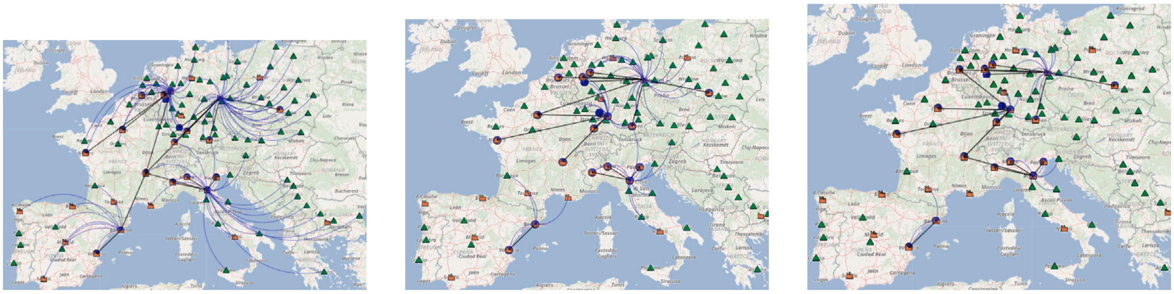
(a) λ = 25%. (b) λ = 41%.

Fig. 4. Change network due to lambda increase.

Table 8
Facility locations and cost breakdown for varying recycling efficiency.

η	#	Locations	Fixed	Variable	Collection	Distribution	**Total**
34%	4	Barcelona, Bologna, Geithain, Dortmund	20,153,900	3,116,100	10,895,700	4,636,000	38,801,700
40%	4	Barcelona, Bologna, Geithain, Dortmund	20,153,900	3,116,100	9,697,500	4,636,000	36,092,300
56%	4	Barcelona, Bologna, Geithain, Stuttgart	20,153,900	3,140,200	5,718,600	4,621,000	33,633,700
70%	4	Barcelona, Bologna, Geithain, Stuttgart	20,153,900	3,121,900	4,543,700	4,580,600	32,400,100
90%	4	Barcelona, Bologna, Geithain, Stuttgart	20,153,900	3,107,000	3,578,700	4,578,300	31,418,000

Note: The second column denotes the number of facilities, with their specific locations given in the third column. The other columns give an overview of the costs associated to this scenario. All costs are given in euros.



(a) η = 34%. (b) η = 56%. (c) η = 90%.

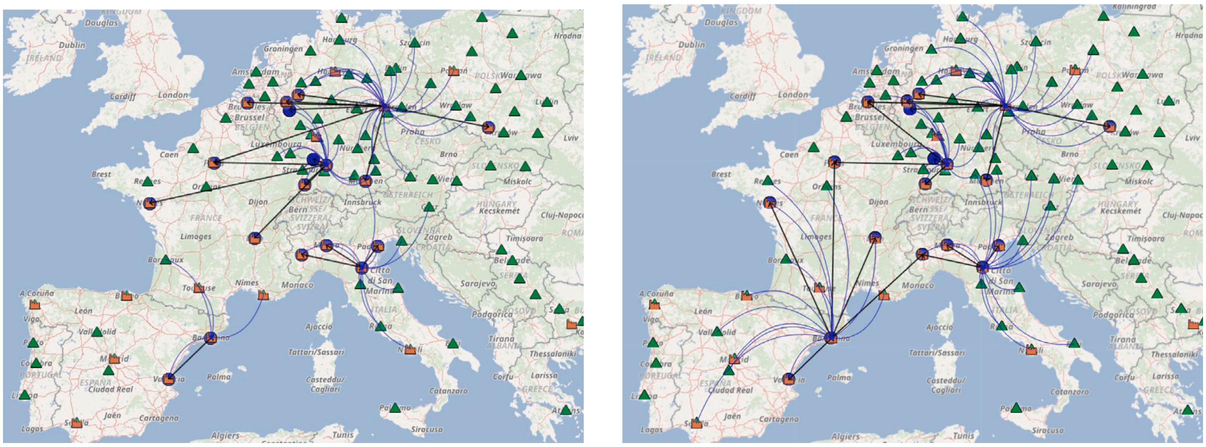
Fig. 5. Change network due to η decrease.

4.5. *Influence of supply and demand fluctuations*

In this section, we first conduct a robustness analysis to evaluate whether the optimized network configurations change under short-term fluctuations in supply and demand. Thereafter, we analyze the long-term feasibility of the optimal network.

We consider a scenario-based sensitivity analysis, where supply and demand for copper waste are perturbed proportionally to their baseline value. This means that when supply (demand) increases in one part of the network, it is also expected to increase in another part of the network. The assumption of correlated supply and demand for copper waste across Europe reflects the shared macro-economic and sectoral drivers underlying both sides of the market. Fluctuations of [−5%, 0, +5%] are considered for supply and demand, leading to a total of 9 scenarios. Given the yearly measurements, fluctuations up to 5% are judged to be realistic and align with past research (Elshkaki et al., 2016; Soares et al., 2025). For 8 out of 9 scenarios, three of the optimal facilities to be opened are Bologna, Geithan, and Stuttgart, with only changes in capacity being observed to address changes in supply and demand. For scenarios where demand remained constant or increased, the Barcelona facility is also opened, whereas for scenarios with a decrease in demand Barcelona remains closed. The only deviating scenario is the one where supply decreases and demand increases, in which case the Stuttgart facility remains closed and a facility in Dortmund is opened instead. In general, the results show to be robust against short-term shocks in supply and demand.

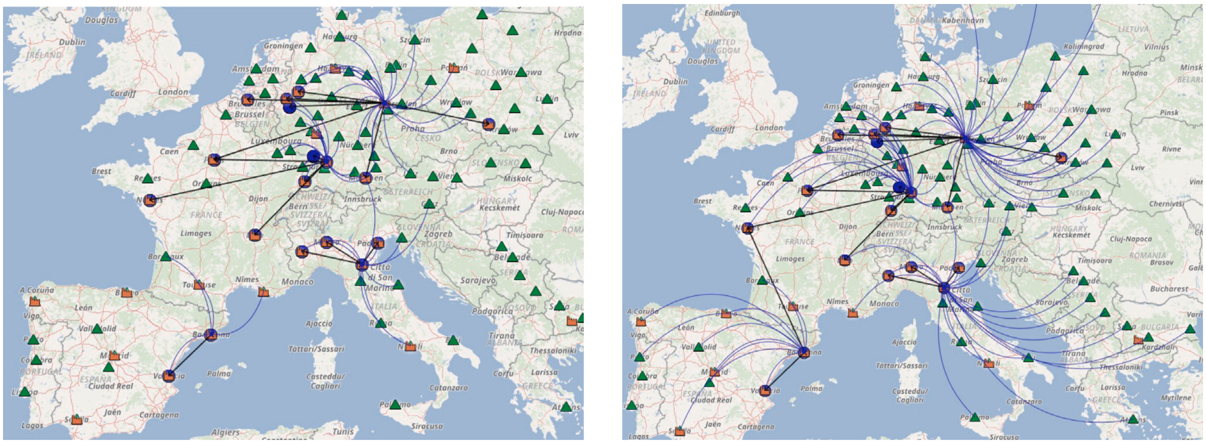
To further analyze the robustness of the network we fix the opened locations, but allow for the production to increase up to the maximum capacity C_{max}. The facilities optimized at baseline demand levels are able to capture a 31.5% increase in demand without opening any



(a) Base case.

(b) Demand increase of 30%.

Fig. 6. Change network due to demand increase.



(a) Base case.

(b) Supply decrease of 39, 5%.

Fig. 7. Change network due to supply decrease.

additional facilities. After that increase, an additional facility would need to be opened. At increased demand, the role of Barcelona has increased significantly as displayed in Fig. 6. In general, all opened facilities extend their reach and collect scrap from further away.

On the other hand, when the supply of scrap materials decreases, the network is feasible down to a 39.5% supply reduction. Below this threshold, copper demand cannot be met with the baseline configuration, and collection costs would rise by 95% (from €5.7M to €11.1M) as waste must be sourced from more distant and scattered locations, increasing transport costs (more sourcing from Eastern Europe, see Fig. 7). Under the threshold, fixed and variable costs remain stable, but facility utilization changes slightly, with Barcelona scaling up to process waste collected from central Spain. The results of this analysis support the results in the previous subsections. For Europe to be resilient against future demand and supply fluctuations, as well as for recycling to be more cost-beneficial, the recycling efficiency needs to be improved.

For both an increase in demand and a decrease in supply, we can observe differences compared to our previous analyses. Whereas locations were allowed to be changed previously, they are fixed at the baseline facilities here. Naturally, a cost increase is therefore observed. Especially, the collection costs increase, given that scrap has to be collected from further away and the facility cannot be relocated to the new geographical center.

5. Conclusion

This research highlights how the Critical Raw Materials Act (CRMA) drives a shift in copper supply chains away from global, cost-driven models towards more EU-based, sustainable networks. Before the CRMA, copper was primarily sourced and processed outside the EU. The CRMA mandates higher EU-based mining, processing, and recycling shares by 2030. Recycling is the most promising solution for meeting CRMA requirements, given the long time needed to build new mines and the environmental concerns associated with new mining projects. Nevertheless, our quantitative analysis highlights that at the current recycling efficiency, at most 41% of the total demand for copper can be satisfied through recycled European copper waste.

The quantitative results indicate that the CRMA in general leads to increased costs. Local recycling is typically more expensive than importing mined or recycled copper. On the contrary, emissions with respect to transportation and mining can be reduced. To quantify this reduction, one would have to evaluate how EU-recycled copper replaces mined copper or recycled copper that was recycled outside the EU. This trade-off depends on company-specific data and decision-making is outside the scope of this work, but marks an important direction of future research. With respect to resilience, the CRMA makes the copper supply chain more resilient against disruptions outside the EU (either at facilities or within the transportation network). However, concentrating recycling in Europe may make the supply chain less resilient against disruptions within the EU. Our analysis shows that a disruption of a single facility may increase costs by up to 25%.

5.1. Policy recommendations

From a policy perspective, the results of this study highlight several important implications. First, regulations such as the CRMA should encourage recycling targets and motivate the design of resilient and diversified recycling networks. The findings demonstrate that while a centralized network is cost-efficient under normal conditions, it becomes vulnerable when disruptions occur, particularly when critical facilities such as Stuttgart or Geithain are impacted. Policymakers could expand recycling infrastructure in underutilized regions like Eastern and Southern Europe. Although these areas do not play an important role in the base case, they show strong potential for enhancing resilience. While central locations contribute to improved performance, they share the same geographical risk exposure as existing sites and may further reinforce centralization rather than promote decentralization. The results show that facility outages lead to unmet demand, which could be mitigated through strategic stockpiling. These buffers would be particularly effective in central hubs that face high demand and limited short-term redundancy.

To support resilient and cost-effective recycling networks, it is important first to explore how existing CRM recycling infrastructure in Europe can be leveraged more effectively. Mapping the current network would help identify where capacity already exists and where upgrades or expansions are possible. This approach reduces the need for new investments and builds on existing capabilities. Furthermore, investment in digitization and advanced logistics systems could improve network adaptability and performance. For instance, establishing real-time waste flow monitoring systems within the EU could serve as coordination and warning tools, enabling action when supply issues arise. Policies could also stimulate collaboration between public and private actors to increase data availability and alignment. Reliable insights into waste availability would allow better recycling throughout Europe.

In addition, to support circular and secure CRM supply chains, domestic recycling must become economically viable. Today, modern devices are not designed for recyclability, making disassembly complex and often unprofitable. Separating copper from mixed waste streams remains a technical challenge, underscoring the need for investment in more effective sorting and pre-separation technologies and highlighting the need for different product designs. An optimized recycling network ensures regulatory compliance, enhances competitiveness, reduces environmental impact, and strengthens Europe's position in the copper industry. However, for this to succeed, policymakers and industry players must address challenges related to waste collection and recycling efficiency. Only then can the copper recycling network evolve into a sustainable and future-proof solution for securing Europe's copper supply. Supported by the results in this paper, further research is needed to increase recycling efficiency to be resilient against regulation changes or a decrease of external copper supply. On top of this, striving for higher recycling efficiencies allows for more cost-effective operations as transportation costs can be reduced significantly.

5.2. Limitations and future research

Future research could refine the model by exploring more nuanced interpretations of the CRMA using fuzzy or probabilistic constraints, reflecting that the 25% recycling target may not apply uniformly at the company level. Additionally, incorporating multi-actor dynamics and accounting for technological and market differences, such as recycling efficiency and price variability, would enhance the model. Future research could extend the proposed modeling framework to other CRMs and broader spatial contexts. While this study focused on copper within the European Union, the underlying MILP formulation and data integration approach are adaptable to other CRMs with appropriate modifications in process yields, transport costs, and regional supply–demand distributions. Additionally, verifying the results with company-specific data is necessary to ensure practical applicability. Lastly, introducing stochastic or robust optimization techniques could address the limitations of the current static and deterministic model by including uncertainties in supply, demand, and disruptions.

Table 9
Dataset of customers.

Customer	Country	Longitude	Latitude	Demand recycled copper (tonnes)
Antwerp	Belgium	4.4028	51.2194	6.872,788
Stuttgart	Germany	9.1829	48.7758	12.042,669
Karlsruhe	Germany	8.4037	49.0069	6.391,189
Freiburg im Breisgau	Germany	7.8522	47.9990	5.937,112
Munich	Germany	11.5761	48.1374	9.009,136
Düsseldorf	Germany	6.7735	51.2277	7.584,976
Cologne	Germany	6.9603	50.9375	6.076,975
Dortmund	Germany	7.4660	51.5136	7.483,414
Barcelona	Spain	2.1734	41.3851	10.575,768
Valencia	Spain	−0.3763	39.4699	5.994,105
Paris	France	2.3522	48.8566	11.023,570
Nantes	France	−1.5536	47.2184	6.775,660
Lyon	France	4.8357	45.7640	10.815,568
Turin	Italy	7.6869	45.0703	6.331,185
Milan	Italy	9.1900	45.4642	15.836,071
Venice	Italy	12.3155	45.4408	9.240,546
Bologna	Italy	11.3426	44.4949	7.823,165
Katowice	Poland	19.0238	50.2649	6.396,520

CRediT authorship contribution statement

Veerle van Citters: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Conceptualization, Investigation, Formal analysis, Data curation. **Arjan van Binsbergen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Patrick Stokkink:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

See Tables 9–12.

Data availability

All data was collected from open sources and are appropriately linked in the manuscript.

Table 10
Dataset of recycling facilities with financial and risk parameters.

Recycling facility	Country	Longitude	Latitude	Fixed costs (€)	Inform risk	Risk class	Risk percentage	Risk costs (€)
Stuttgart	Germany	9.17702	48.78232	189,000,000	2.4	Low	1.0%	1,890,000
Sevilla	Spain	−5.97317	37.38283	145,300,000	2.4	Low	1.0%	1,453,000
Düsseldorf	Germany	6.77616	51.22172	218,000,000	2.4	Low	1.0%	2,180,000
Paris	France	2.3488	48.85341	261,600,000	2.9	Low	2.0%	5,232,000
Nantes	France	−1.55336	47.21725	145,300,000	2.9	Low	2.0%	2,906,000
Lyon	France	4.84671	45.74846	189,000,000	2.9	Low	2.0%	3,780,000
Milan	Italy	9.18951	45.46427	218,000,000	2.5	Low	1.2%	2,616,000
Venice	Italy	12.33265	45.43713	218,000,000	2.5	Low	1.2%	2,616,000
Katowice	Poland	19.02754	50.25841	116,300,000	2.5	Low	1.2%	1,395,600
Freiburg	Germany	7.85222	47.9959	189,000,000	2.4	Low	1.0%	1,890,000
Darmstadt	Germany	8.58874	49.9039	189,000,000	2.4	Low	1.0%	1,890,000
Hannover	Germany	9.73322	52.37052	189,000,000	2.4	Low	1.0%	1,890,000
Dortmund	Germany	7.466	51.51494	189,000,000	2.4	Low	1.0%	1,890,000
Geithain	Germany	12.69674	51.05528	116,300,000	2.4	Low	1.0%	1,163,000
Rakitovo	Bulgaria	24.0873	41.99012	87,200,000	2.7	Low	1.6%	1,395,200
S. de Compostela	Spain	−8.54569	42.88052	145,300,000	2.4	Low	1.0%	1,453,000
Bilbao	Spain	−2.92528	43.26271	145,300,000	2.4	Low	1.0%	1,453,000
Madrid	Spain	−3.70256	40.4165	145,300,000	2.4	Low	1.0%	1,453,000
Valencia	Spain	−0.37739	39.46975	145,300,000	2.4	Low	1.0%	1,453,000
Toulouse	France	1.44367	43.60426	145,300,000	2.9	Low	2.0%	2,906,000
Marseille	France	5.37034	43.29664	189,000,000	2.9	Low	2.0%	3,780,000
Turin	Italy	7.68682	45.07049	189,000,000	2.5	Low	1.2%	2,268,000
Naples	Italy	14.26811	40.85216	145,300,000	2.5	Low	1.2%	1,743,600
Bologna	Italy	11.33875	44.49381	145,300,000	2.5	Low	1.2%	1,743,600
Poznań	Poland	16.92993	52.40692	116,300,000	2.5	Low	1.2%	1,395,600
Uppsala	Sweden	17.63889	59.85882	218,000,000	1.9	Very Low	0.5%	1,090,000
Göteborg	Sweden	11.96679	57.70716	218,000,000	1.9	Very Low	0.5%	1,090,000
Antwerpen	Belgium	4.40346	51.21989	218,000,000	2.1	Low	0.8%	1,744,000
Munich	Germany	11.57549	48.13743	218,000,000	2.4	Low	1.0%	2,180,000
Barcelona	Spain	2.17628	41.38364	145,300,000	2.4	Low	1.0%	1,453,000

Table 11
Transport costs data ($B_{j1} = B_{1k}$) - 25 tonnes load (Persyn et al., 2022).

City	Transport costs (€/km)	Transport costs (€/ton/km)
Stuttgart	1.596	0.0638
Sevilla	5.921	0.2368
Düsseldorf	1.596	0.0638
Paris	2.046	0.0818
Nantes	2.279	0.0912
Lyon	2.046	0.0818
Milan	2.046	0.0818
Venice	2.046	0.0818
Katowice	1.596	0.0638
Freiburg	1.746	0.0698
Darmstadt	1.596	0.0638
Hannover	1.596	0.0638
Dortmund	1.596	0.0638
Geithain	1.746	0.0698
Rakitovo	2.514	0.1006
S. de Compostela	2.893	0.1157
Bilbao	2.893	0.1157
Madrid	2.514	0.1006
Valencia	2.893	0.1157
Toulouse	2.510	0.1004
Marseille	2.046	0.0818
Turin	2.046	0.0818
Naples	2.279	0.0912
Bologna	2.046	0.0818
Poznań	1.746	0.0698
Uppsala	5.921	0.2368
Göteborg	5.921	0.2368
Antwerpen	1.746	0.0698
Munich	1.746	0.0698
Barcelona	2.893	0.1157

Table 12
Variable costs data (v_i).

Country	Labor costs	Costs (€/ton)
Germany	€41.3/h	23.33/ton
Bulgaria	€9.3/h	5.25/ton
Spain	€24.6 h	13.90/ton
France	€42.2/h	23.84/ton
Italy	€29.8/h	16.84/ton
Poland	€14.5/h	8.19/ton
Belgium	€47.1/h	26.61/ton
Sweden	€38.9/h	21,98/ton

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